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PLANT CHARACTERISTICS OF A MULTI-FUEL SOFC-STIRLING HYBRID CONFIGURATION

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ABSTRACT

A novel hybrid system (~10 kWe) for an average family house including heating is proposed. The system investigated, contains of a Solid Oxide Fuel Cell (SOFC) on top of a Stirling engine. The off-gases produced in the SOFC cycle is fed to the bottoming Stirling engine wherein additional power is generated. Simulations for the proposed system were conducted using different fuels which facilitate use of variety of fuels depending on availability. Here, results for Natural Gas (NG), ammonia, Di-Methyl Ether (DME), methanol and ethanol are presented and analysed. System behaviour is further investigated by comparing the effects of key factors such as: utilisation factor, operating conditions, Oxygen-to-Carbon (O/C) ratios and fuel preheating effects on these fuels. Moreover, effect of Methanator on plant efficiency is also studied. The combined system improves the overall electrical conversion efficiency compared with the stand alone Stirling engine or SOFC plant. For the SOFC and Stirling combined configuration, the overall power production has increased by about 10% compared to the stand alone SOFC plant. System efficiencies of about 60% are achieved which is remarkable for such small plant sizes. Additionally, heat is also produced for heating the family house whenever it is needed.

Keywords: *SOFC, Stirling, fuel cell, hybrid systems, system efficiency, multi-fuel*

1 INTRODUCTION

High temperature fuel cells (In particular SOFC) have shown a significant potential as a viable solution for power production. The hybrid SOFC system is considered to be a key technology in achieving the goals of the future on account of the many advantages it offers over other systems [1]. Firstly, SOFC does not contain any moving parts. Noise and vibrations during operation are practically non-existent, making it possible to install the system in urban areas. Non-mechanical parts also assure high reliability and low maintenance costs. Secondly, SOFCs can operate on a variety of fuels and are more resistant to electrode poisoning. It can tolerate sulfur compounds at concentrations higher than other types of fuel cells. In addition, unlike most of fuel cells, CO can be used as a fuel in SOFC. Due to the above mentioned advantages, SOFC is considered to be a strong candidate for hybrid systems or integration into currently deployed technologies.

SOFC-based hybrid power plants have been proposed by researchers with extensive studies on integration of SOFC in Gas Turbine (GT) and steam turbine (ST) power plants, whereas studies on prospects of combining SOFC with a Stirling engine are limited. Although, SOFC–GT and SOFC–ST power plants display high efficiencies, their operations are limited to large-scale plants only. Combined SOFC–Stirling plants offer a viable potential for small-scale CHP (Combined Heat and Power) generation units due to the fact that they have rapid start-up times. However, capital cost of SOFC and Stirling turns out to be the major obstacle in commercialization of these plants. This study is an effort to investigate the feasibility of a small-scale SOFC-Stirling power plant. The feasibility of a mobile SOFC-Stirling hybrid system is discussed in [2], without presenting any thermodynamic simulation of the system.

In this study a small scale SOFC-Stirling CHP (Combined Heat and Power) plant is presented and thermodynamically analyzed. Detail plants configurations fueled with variety of fuels are presented and calculated. Fuels that are used in this investigation are NG (Natural Gas), Methanol, Ethanol, DME and ammonia. The plant configuration for NG is the most complicated one in which a desulfurizer reactor and a pre-reformer reactor are included. The desulfurizer unit removes the sulfur content in the gas and the pre-reformer converts the heavier hydrocarbons (other hydrocarbons than methane) into methane, mono-carbon and hydrogen. The plant for methanol, ethanol and DME includes a Methanator in which the idea is to increase the composition of methane when the fuel is reacted with steam. The plant for ammonia is the simplest one since fuel can be fed to SOFC cells directly.

The gases after the anode side of the SOFC have still some fuel which can be sent to the burner of the Stirling engine. The Stirling engine used here is a small scale (1-5 kW) engine which is under developed by

some company such as StirlingDK. The engine is cooled by water and the water circulate in all the spaces of the house and heat up the house by floor heating. The forward water temperature is about 40°C which is suitable for family house with floor heating. Alternatively, radiators can be used if the forward temperature of water is allowed to be increased to 45-50°C. The off-gases after the Stirling engine are used to heat up the water consumption in the house (showering, washing, etc.).
It should also be noted that the system presented here was studied thermodynamically and the objective of this study was not to present or discuss associated costs. Plants performances were compared to each other in terms of efficiency, fuel consumption and other related parameters.

2 METHODOLOGY

The results of this paper are obtained using the simulation tool dynamic network analysis (DNA), which is a simulation tool for energy system analysis [3]. In DNA, the physical model is formulated by connecting the relevant component models through nodes and by including operating conditions for the complete system. The physical model is converted into a set of mathematical equations to be solved numerically. The mathematical equations include mass and energy conservation for all components and nodes as well as relations for thermodynamic properties of the fluids involved. At the end each component the equations for energy balance and mass balance are included. The total mass balance and energy balance for the entire system will also be accounted. The program is written in FORTRAN.

2.1 Modelling of SOFC

The SOFC model developed in this investigation is based on the planar type developed by DTU-Risø and TOPSØE Fuel Cell (TOFC). The model was calibrated against experimental data in the range of 650°C to 800°C (operating temperature) as described in [4]. The operational voltage (E_{FC}) was found to be the summation of Nernst ideal reversible voltage, activation polarization, ohmic polarization and concentration polarization. The activation polarization was evaluated from the Butler–Volmer equation by isolating it from other polarizations to determine the charge transfer coefficients and exchange current density from the experiment by the curve fitting technique. The ohmic polarization depends on the electrical conductivity of the electrodes as well as the ionic conductivity of the electrolyte and was expressed based on anode thickness, electrolyte thickness, cathode thickness and current density. The concentration polarization is dominant at high current densities for anode-supported SOFCs, wherein insufficient amounts of reactants are transported to the electrodes and the voltage is then reduced significantly. It was modeled as function of diffusion coefficient, anode limiting current and current density. The anode limiting current was modeled as function of anode porosity, anode tortuosity and a binary diffusion coefficient. Both The diffusion coefficient and the binary diffusion coefficient were calibrated against experimental data. Finally the current density is directly proportional to the amount of reacting hydrogen and the cell area, according to Faraday's law. The fuel composition leaving the anode was calculated by the Gibbs minimization method. The power production from the SOFC (P_{SOFC}) depends on the amount of chemical energy fed to the anode, the reversible efficiency (η_{rev}), the voltage efficiency (η_v) and the fuel utilization factor (U_F). U_F was a set value while the reversible efficiency is the maximum possible efficiency defined as the relationship between the maximum electrical energy available (change in Gibbs free energy) and the fuels LHV (lower heating value) as explained in [1]. The main parameters for SOFC are given in Table 1.

2.2 Modelling of Stirling Engine

The Stirling engine is noted for its quiet operation and the ease with which it can use almost any heat source. In this study, a pseudo Stirling cycle which has a better agreement to engine performance data is developed, [5]. The main difference between the pseudo Stirling cycle and the ideal Stirling cycle is the assumption of isentropic compression and expansion rather than isothermal compression and expansion. Assuming isentropic compression and expansion provide more realistic cycle performance since in this way losses encountered in the Stirling engine will be accounted. In modeling, the engine is divided into three parts, heater, engine and a cooler. The heater is modeled as a heat exchanger where the cold side (the heater wall, T_{hw}) is assumed to have a constant temperature which has to be given. The most important parameters of a Stirling engine are the temperature ratio ζ, the compression ratio ξ, the regenerator effectiveness ε_r and the heater effectiveness ε_h. These are defined as

$$\zeta = \frac{T_1}{T_3} \quad , \quad \xi = r_v = \frac{V_4}{V_3} \quad , \quad \varepsilon_r = \frac{T_2^{'} - T_1}{T_3 - T_1} \quad , \quad \varepsilon_h = \frac{T_{hot,in} - T_{hot,out}}{T_{hot,in} - T_{hw}} \qquad (1)$$

where *T* and *V* stands for the temperature and volume respectively. The subscripts 1 stands for the state at inlet (inlet of working fluid), 2 stands for state after compression, 3 stands for the state after heating and 4 stands for the state after cooling. The state $T_2^{'}$ corresponds to state where the heating process is divided into isochoric heating of the regenerator and isochoric heating of the heater, see [6] for further details. The efficiency of such pseudo Stirling engine can be written as

$$\eta_{Stirling} = \frac{\left[\left(1-\xi^{1-\gamma}\right)-\zeta\left(\xi^{1-\gamma}-1\right)\right]}{\left[\left(1-\xi^{1-\gamma}\right)+\left(1-\zeta\right)\left(1-\varepsilon_r\right)\right]} \qquad (2)$$

where γ is the ratio of the specific heats. The work of Stirling engine is found from the engine efficiency

$$W_{Stirling} = \eta_{Strirling}\left(\dot{Q}_{high} - \dot{Q}_{loss}\right) \qquad (3)$$

where $\dot{Q}_{high}$ and $\dot{Q}_{loss}$ are the heat added by the heater and the heat removed from the engine. Note that heat added and heat lost from the engine are done in two different heat exchangers. The losses from the Stirling engine are the result of various losses; mechanical and thermal losses. The heat loss from the engine is estimate by

$$\dot{Q}_{loss} = \left(1 - f_{loss}\right)\dot{Q}_{high} \qquad (4)$$

wherein f_{loss} is the "loss factor" which incorporates all different losses in the engine, mechanical as well as thermal losses. This loss factor is similar to an efficiency which will be 100% if there are no losses. Such approach modeling provides reasonable results when compared with the experimental data of a Stirling engine is very simple but will still give reasonable results, if floss is calibrated from performance data. In Eq. (9) T_1 is the lowest temperature (cooler wall temperature, T_{cw}) and T_1 is the highest temperature (working fluid temperature inside the engine, T_{hg}). These temperatures are calculated by

$$T_{hg} = T_{hw} - \Delta T_{heater} \quad , \quad T_{cw} = T_{cw,in} + \frac{2}{3}\Delta T_{cooler} \qquad (5)$$

Thus working fluid (helium) highest temperature is smaller than the heater wall temperature and its lowest temperature is a weighted temperature between inlet and outlet. The main parameters for Stirling engine are given in Table 2.

Table 1. SOFC main parameters for design case.

Fuel utilization factor	0.80
Number of cells in stack	74
Number of stacks	10
Cathode pressure drop ratio, (bar)	0.05
Anode pressure drop ratio, (bar)	0.01
Cathode inlet temperature, (˚C)	600
Anode inlet temperature, (˚C)	650
Outlet temperatures, (˚C)	780
Generator efficiency	0.97

Table 2. Stirling engine main parameters for design case.

Heater and cooler Δp, (bar)	0.01
Heater wall temperature, (˚C)	600
Heater ΔT, (˚C)	125
Heater effectiveness	0.95
Cooler ΔT, (˚C)	60
Compressor ratio, (–)	1.44
Regenerator effectiveness	0.98
Mechanical loss factor	0.8

2.3 Modelling of Reformer and Methanator

To model the pre-reformer and Methanator a simple Gibbs reactor is implemented [7], meaning that the total Gibbs free energy has its minimum when chemical equilibrium is achieved. Such characteristic can be used to calculate the outlet gas composition at a specified temperature and pressure without considering the reaction pathways. However, the species at outlet must be specified, which can be different from Methanator

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to a pre-reformer. The species at outlet of both pre-reformer are denied and as; H_2, CO, CO_2, steam, CH_4, N_2, NO, H_2S, SO_2, NO_2, NH_3 and Ar. For the Methanator the species at outlet of are denied and as; H_2, CO, CO_2, steam, CH_4, N_2, NO, H_2S, SO_2, NO_2, HCN (hydrogen cyanide), COS (carbonyl sulfide), N_2O, NO_3, SO_3 and Ar.

2.4 Modelling of Other Components

The pumps power consumption were calculated as

$$W_{pump} = \left[\frac{\dot{m}\upsilon_{in}(p_{out} - p_{in})}{\eta}\right]_{pump}, \quad \eta_{is} = \left[\frac{h_{out,Sin} - h_{in}}{h_{out} - h_{in}}\right]_{compressor}, \quad \eta_m = \left[\frac{\dot{m}(h_{out} - h_{in})}{W}\right]_{compressor} \tag{7}$$

where $\dot{m}$, p, υ and η were the mass flow, pressure, specific volume (m^3/kg) and efficiency of the pump respectively. h_{Sin} was the enthalpy when entropy kept constant as for inlet. In modeling a heat exchanger, it was assumed that all energy from one side is transferred to the other side if heat losses were neglected. The desulfurizer unit is a simple model in which the sulfur content is removed. The compositions will be re-calculated after removing sulfur. Main parameters for accessory components are given in Table 3.

Table 3. Main parameters for accessory components

Compressor intake temperature, (˚C)	25
Compressor isentropic efficiency	0.7
Compressor mechanical efficiency	0.95
Fuel side heat exchangers Δp, (bar)	0.01
Air/Gas side heat exchangers Δp, (bar)	0.05
Water side heat exchangers Δp, (bar)	0.3
Desulfurizer temperature, (˚C)	200
Depleted air temperature, (˚C)	40
Depleted exhaust gas temperature, (˚C)	95
Fuel inlet temperature, (˚C)	25

3 PLANTS CONFIGURATIONS

The proposed combined power system constitutes a SOFC and Stirling system connected in series. The fuel is fed to the topping SOFC cycle only, where the fuel reforming and the electrochemical oxidation processes occur. The SOFC stack produces electrical power together with an exhaust stream that contains unused CO and H_2. These unburned fuels from the anode side together with the exhaust air from the cathode side are the sent to a burner straight away for further combustion. Simulations for the plant are conducted using different fuels; natural gas (NG), DME, ethanol, methanol and ammonia. The configuration of SOFC plant is different depending on the nature of the fuel. Whereas, Stirling plant retains the same configuration as it is only operated by heat generated form the exhaust gases from the burner and a cooling circuit. Three configurations are suggested for the combined SOFC-Stirling system; the first configuration with natural gas as fuel is shown in Figure 1a. The fuel is preheated to 200°C before it is sent to a desulphurization unit. As known, SOFCs are capable of direct internal reforming of light hydrocarbons (such as methane) at the anode but not the heavier hydrocarbons. Using high operating temperature, methane can be directly reformed to H_2 and CO. Due to small amount of heavier hydrocarbons in NG an external reforming system is employed to avoid thermal shock caused by the endothermic reforming reaction. The heavier hydrocarbons in the NG are reformed in a CPO (Catalytic Partial Oxidation) type pre-reformer reactor. Another heat exchanger heats the fuel to the designated temperature of the pre-reformer. Due to the exothermic nature of the CPO reactions, the outlet temperature is high enough to support direct feeding into the SOFC. However, for the sake of security a heat exchanger is included to ensure that pre-reformed fuel as a temperature of at least 650°C before entering the anode side of SOFC. The operating temperature of the SOFC stacks is assumed to be 780°C which is also assumed as the outlet temperature of the SOFC cells, both anode and cathode sides. The

thermal energy of exhaust fuel is recuperated for heating the incoming fuel at all the stages mentioned above.

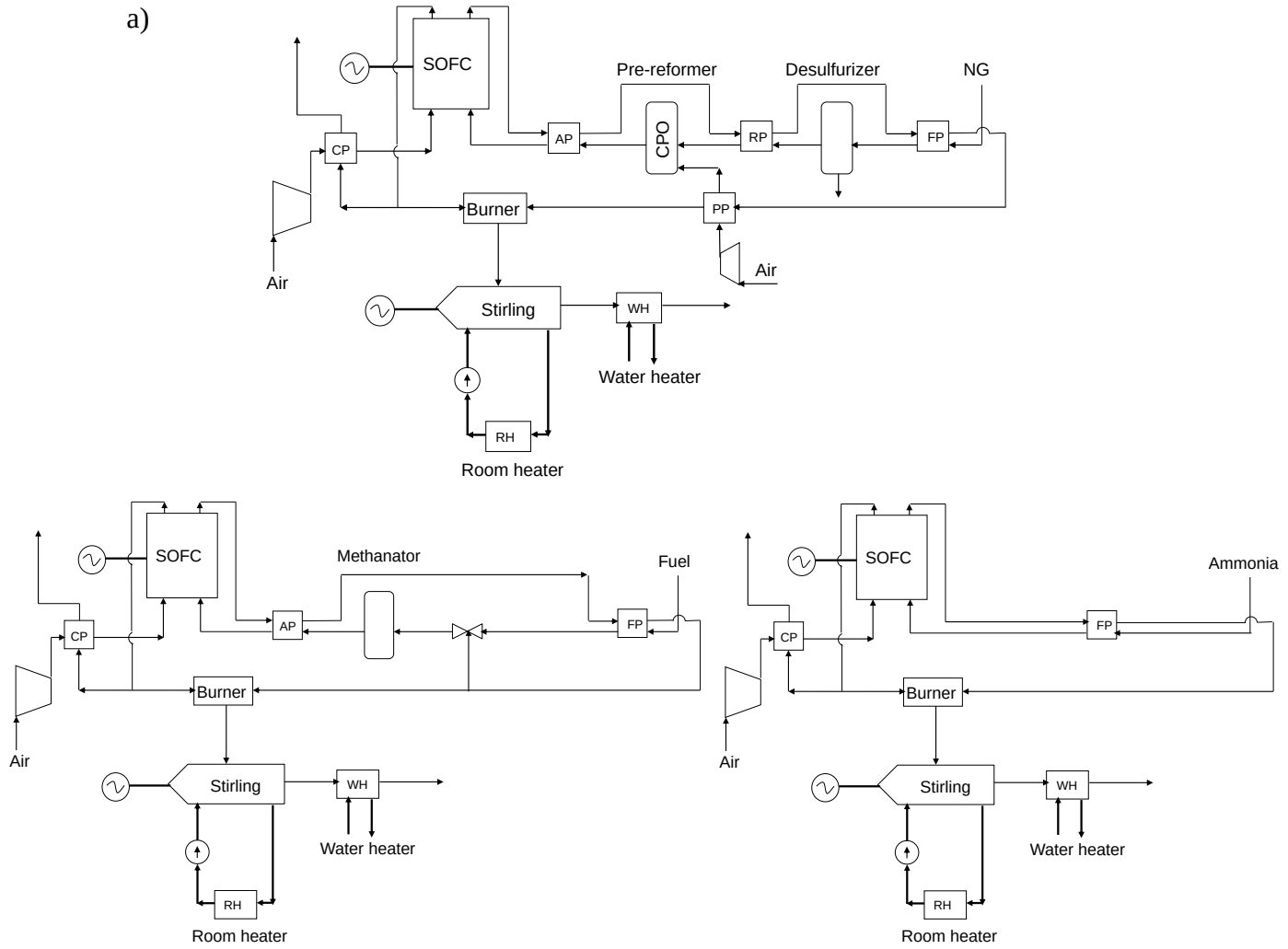

Figure 1. Schematics of combined SOFC–Stirling plants, (a) For natural gas as fuel and (b) For Methanol, DME and Ethanol as fuels, (c) For ammonia as fuel.

For the cathode side of the SOFC, air is compressed preheated in a heat exchanger to about 600°C. The electrochemical reactions at anode and cathode produce electrical power and heat at the expense of the fuel. Part of the heat that is released is utilized in the endothermic reforming process. The depleted fuel still contains some unutilized combustible fuel, such as hydrogen and carbon monoxide, is sent to a burner to generate heat for the bottoming Stirling cycle. The cooling circuit of the Stirling engine contains a heat exchanger which heats up all the spaces (rooms) of the family house. This heat exchanger is designated as RH (room heater) in the figure. Thus the burner acts as a heat source for the Stirling engine while the RH acts as heat sink for the Stirling engine. The exhaust gases after the Stirling engine has still valuable heat which can be used for warming up the hot water consumption in the house; such as hot water for showering and washing. This heat exchanger is designated as WH (Water Heater) in the figure.

The schematic of the second configuration is shown in Figure 1b. DME, ethanol and methanol are used as fuels in this configuration. Unlike natural gas, these fuels do not require any desulphurization unit. Also, a Methanator is used for cracking the fuel and increasing the amount of methane. Due to endothermic nature of methane reforming inside the SOFC stacks, the need for excess air to cool down the SOFC stacks will decrease. This in turn decreases the air compressor work and thereby increases the plant efficiency. The fuel is preheated before the Methanator where it is reformed to CH_4, H_2 and CO. Another heat exchanger heats the fuel to the desired temperature for the SOFC inlet after the Methanator. Some part of exhaust fuel from the SOFC is recycled and mixed with the incoming fuel to provide steam for the Methanator. For the high temperature recycle pump, long term durability is a problem. On the other hand for the low temperature

pump, the off-fuel stream is needed to be cooled to a low temperature which results in wastage of substantial thermal energy. In this study, an ejector is employed for simulations. Rest of the plant configuration remains the same as in the NG case.

For the third configuration the schematic is shown in Figure 1c, in which ammonia is used as fuel. Since ammonia can be fed to the SOFC cells directly then unlike NG. Rest of the plant remains the same as in the previous cases.

4 RESULTS AND DISCUSSIONS

It is important to mention here that net power output of the plant was affixed to 10 kW for all the fuels. All power inputs and outputs, species flows, heat losses and heat sources were balanced in the simulations making the modeled plants thermally self-sustainable i.e. no extra heat or fuel was needed. The fuel is fed only to the SOFC cycle. Since Stirling engine extracts fuel from SOFC exhaust stream, fuel feed remains the same for both the plants. Some vital results are presented and discussed below. Main calculated parameters are shown in Table 4.

Table 4. Calculated parameters for the hybrid plant.

Parameter	NG	DME	Ethanol	Methanol	Ammonia
Fuel mass flow, (kg/hr)	1.33	2.14	2.16	3.09	3.78
SOFC off-fuel, (kg/hr)	6.44	5.90	5.98	7.05	7.93
Air compressor mass flow, (kg/hr)	58.44	61.15	52.49	71.78	61.37
Burner temperature, (˚C)	1255.9	1304.6	1346.6	1199.7	1149.0
CPO/Methanator inlet T, (˚C)	525	300	300	300	–
CPO/Methanator outlet T, (˚C)	650	594	528	566	–
Fuel recirculated to Methanator, (%)	–	7.7	3.2	3.3	–
Stirling outlet temperature, (˚C)	632.8	635.2	637.3	630.0	627.5
Stirling power, (kW)	1.105	1.183	1.129	1.223	1.203
Thermal efficiency, (%)	59.03	58.57	62.61	59.02	57.60

One of the observable differences is that methanol uses more air to produce 10kW electricity than other fuel and while NG has the highest air-fuel ratio. On the other hand, least amount of air is compressed for SOFC when ethanol is used as a fuel. This is due to the fact that reformed-ethanol has high levels of methane (CH_4) which lead to more internal reforming (endothermic reactions) in SOFC when compared to other fuels and consequently, less air is needed to cool down the stack. Moreover, in contrast to NG, higher percentages of water in the reformed ethanol promote endothermic reforming in the fuel cell. It can also be observed that the Methanator temperature is the lowest for ethanol. The plant efficiency for the ethanol is highest while ammonia plant has the lowest efficiency.

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